Recent results in semileptonic B decays at LHCb

21$^{\mathrm{st}}$ International Conference on *B*-Physics at Frontier Machines, "BEAUTY 2023"

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on behalf of the LHCb Collaboration

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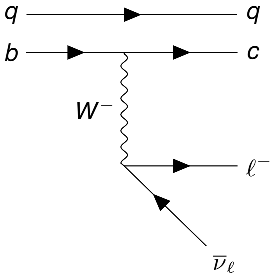
Recent semileptonic results from LHCb in 2020s



- Measurement of the D^* longitudinal polarization NEW!
  LHCb-PAPER-2023-020 in preparation
- Measurement of $R(D^*)$ hadronic
  Accepted by PRD arXiv:2305.01463
- Combined $R(D)$ and $R(D^*)$ muonic
  Accepted by PRL arXiv:2302.0288

- Observation of the Decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ *PRL 128.191803 (2022)*

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- Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$ decays *PRD 101 (2020) 072004*
- Observation of the semileptonic decay $B^+ \to p\bar{p}\mu^+\nu_\mu$ *JHEP 2003 (2020) 146*
- First observation of the decay $B_s \to K^- \mu^+ \nu_\mu$ and measurement of $|V_{ub}|/|V_{cb}|$ *PRL 126.081804 (2021)*
- Observation of a Λ_b^0-$\overline{\Lambda}_b^0$ production asymmetry in proton-proton collisions *JHEP 2110 (2021) 060*

- Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$ decays *PRD 101 (2020) 072004*

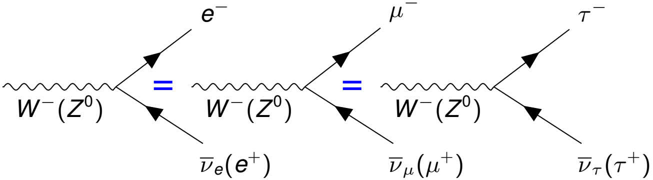
- Measurement of the shape of the $B_s^0 \to D^{*-} \mu^+ \nu_\mu$ differential decay rate *JHEP 2012 (2020) 144*

- Observation of the semileptonic decay $B^+ \to p\bar{p}\mu^+\nu_\mu$ *JHEP 2003 (2020) 146*

LFU measurements

Lepton Flavour Universality

- Within the Standard Model (SM), the weak interactions towards three generations of leptons are identical



- New physics (NP) may be more sensitive to the 3rd family
- Three typical candidates for NP:
  - **leptoquarks** PRD 94, 115021, ...
  - **two Higgs doublet models** PRL 116, 081801, ...
  - **Heavy vector bosons**, e.g. W' JHEP 07 (2015) 142 1506.01705, ...
- Need to cancel for theoretical uncertainties:

$\Longrightarrow$ measure ratios of $\mathcal{B}$

Charged current $b \to c\ell\nu_\ell$

- Main contribution:
  tree level diagrams

$$R(X_c) \equiv \frac{\mathcal{B}(X_b \to X_c\tau^+\nu_\tau)}{\mathcal{B}(X_b \to X_c\ell^+\nu_\ell)}$$

$$X_b = B^{0,+}_{(s,c)}, \Lambda^0_b, \qquad \ell = \mu, e,$$
$$X_c = D^{(*)}_{(s)}, J/\psi, \Lambda^+_c$$

Neutral transition $b \to s\ell\ell$

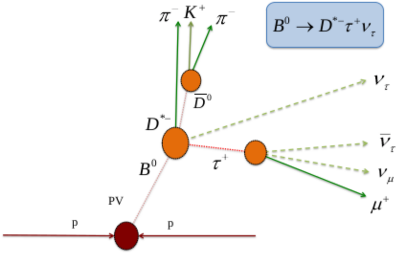
- Main contribution:
  penguin or box diagrams

$$R(X_s) \equiv \frac{\mathcal{B}(X_b \to X_s\mu^+\mu^-)}{\mathcal{B}(X_b \to X_s e^+e^-)}$$

(X_b, X_s) = (B^0, K^{*0}) or (B^+, K^+)

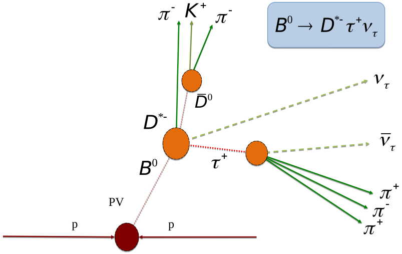
$R(X_c)$ measurements at LHCb

Muonic τ decay



- Direct measurement of $R(X_c)$
- High statistics
- Backgrounds from D^+ must be controlled well
- Sensitive to $D^{**}\mu^-\nu_\mu$

Hadronic τ decay



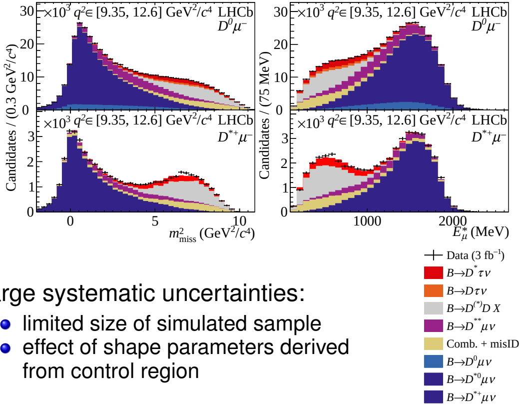
- Measuring τ^+ decay position to suppress dominant backgrounds
- High purity sample
- Specific dynamics of $\tau^+ \to 3\pi^\pm\bar{\nu}_\tau$
- $R(X_c)$ requires external inputs
- Lower statistics

Combined $R(D)$ and $R(D^*)$ muonic at LHCb [arXiv:2302.02886]

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data using muonic τ decays

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}, \qquad \tau^- \to \mu^-\nu_\mu\nu_\tau, \qquad D^{*-} \to D^0(\to \pi^+K^-)\pi^-$$

- Maximum likelihood fit to (2×) isolated signal regions and (2 × 3×) anti-isolated control regions
- Using rest frame approximation, construct 3D template histograms:
    - $q^2 \equiv (p_B - p_{D^*})^2$
    - $m^2_{miss} \equiv (p_B - p_{D^*} - p_\mu)^2$
    - E^*_μ energy of μ



$$R(D) = 0.281 \pm 0.018(stat) \pm 0.024(syst)$$
$$R(D^*) = 0.441 \pm 0.060(stat) \pm 0.066(syst)$$

1.9σ above the SM

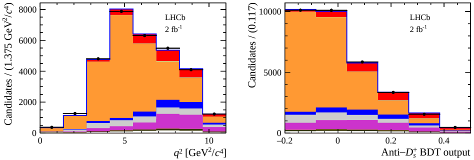
- Large systematic uncertainties:
    - limited size of simulated sample
    - effect of shape parameters derived from control region

$R(D^*)$ hadronic at LHCb [arXiv:2305.01463, PRD 97, 072013 (2018)]

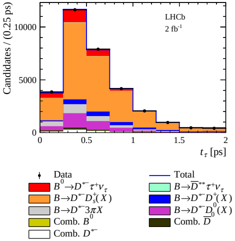
- Measurement of $R(D^*)$ with partial Run 2 data using hadronic τ decays

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}, \qquad R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \right\}_{external}$$

- Fit performed using 3D binned template
  - $q^2 \equiv (p_{B^0} - p_{D^*})^2$
  - τ decay-time
  - anti-D_s BDT output
- Main background:
  - prompt $B \to D^* 3\pi^\pm X$ (strongly suppressed)
  - double charm $B \to D^* D_{(s)}(\to 3\pi^\pm X)X'$



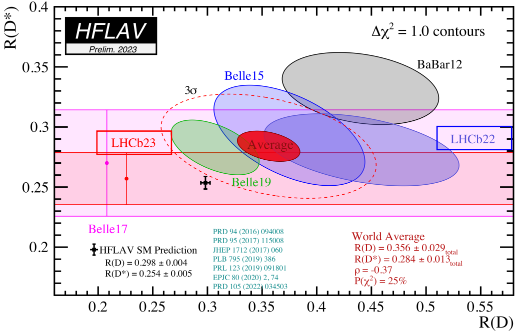
$$R(D^*)_{Run\ 2} = 0.247 \pm 0.015(stat) \pm 0.015(syst) \pm 0.012(ext)$$
$$R(D^*)_{Run\ 1-2} = 0.257 \pm 0.012(stat) \pm 0.014(syst) \pm 0.012(ext)$$

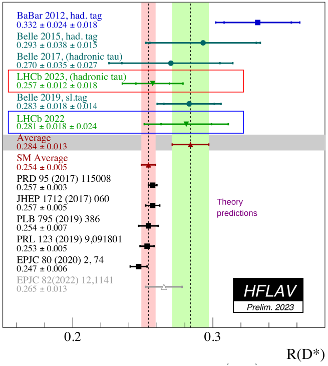


Agreement to SM within 1σ

- Main systematic uncertainties:
  - limited size of simulated samples
  - signal/background modelling

Current $R(D) - R(D^*)$ scenario [**HFLAV**]





- Discrepancy of the WA of $R(D^*)$ with SM 1.9σ
- Deviation of the $R(D) - R(D^*)$ combination: 3.2σ

$F_L^{D^*}$ measurement in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

Longitudinal D^* polarization

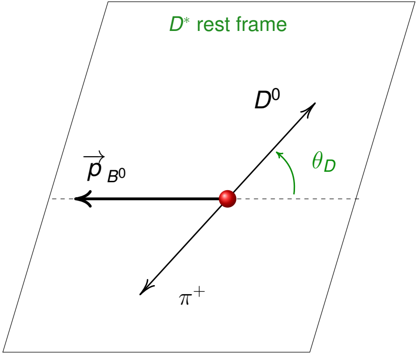
- Measurement of the longitudinal D^* polarization can provide complementary information to $R(D^*)$, showing NP contribution even if $R(D^*)$ is found compatible with SM expectation

- The differential decay rate can be expressed as 2° polynomial in $\cos\theta_D$:

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

  - D^* longitudinal polarization fraction as function of $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$:

$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$



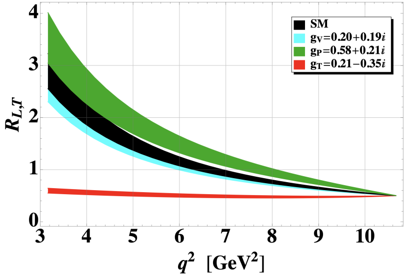
- State of art is determined by Belle results:

$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

axXiv:1903.03102

Expected value of F_l^D

- $F_L^{D^*}$ value within the SM scenario has been predicted with different methods
- The most recent theoretical predictions are:
    - 0.441 ± 0.006 arXiv:1808.03565 *Zhuo-Ran Huang, Ying Li, Cai-Dian Lu, M. Ali Paracha, Chao Wang*
    - 0.457 ± 0.010 arXiv:1805.08222 *Srimoy Bhattacharya, Soumitra Nandi, Sunando Kumar Patra*
- Predictions for NP scenarios can be found in arXiv:1907.02257
  Damir Becirevic, Marco Fedele, Ivan Nisandzic, Andrey Tayduganovd



arXiv:1907.02257

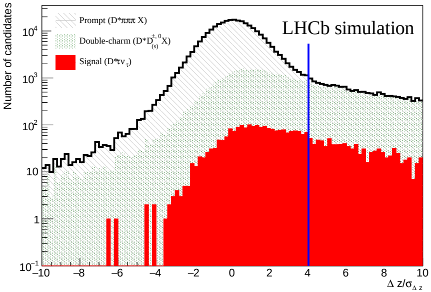
- Expected dependence of $R_{L,T}$ as function of q^2 for three NP models

$$R_{L,T}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

$$F_L^{D^*}(q^2) = \frac{R_{L,T}(q^2)}{1 + R_{L,T}(q^2)}$$

Signal selection

- Analysis performed using hadronic τ decays
- Same strategy used in the $R(D^*)$ hadronic
- Simultaneous fit on 2011-12 (Run 1) and 2015-16 (Run 2) data



[Phys. Rev. D 97, 072013]

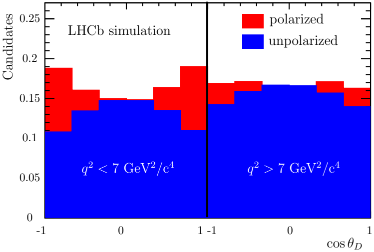
- Advantages of hadronic the decay mode:
  - only 1 neutrino in the τ decay:
    $\Longrightarrow$ event kinematic is properly reconstructed
  - good purity $\Longrightarrow$ strong background rejection

Initially dominant backgrounds

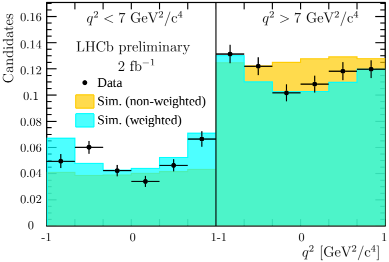
- Prompt decay $B \to D^{*-}3\pi^{\pm}X$
  - 3π system from the B meson
  - $\sim 100\times$ signal decays
  - requiring a 3π vertex detached by the B vertex along the beam axis ($\Delta_z/\sigma_{\Delta_z} > 4$)
  - additional BDT in Run 2 to reach Run 1 rejection level: > 99.9%
- Double charm $B \to D^{*-}D_{(s)}^{+,0}X$ decays
  - signal like topology
  - detached vertex due to non-negligible lifetime
  - rejected through isolation algorithm and dedicated MVA classifiers

Signal & background description [LHCB-PAPER-2023-020]

- $F_L^{D^*}$ determined in two q^2 regions: $\lessgtr 7\ \text{GeV}^2/c^4$
- $F_L^{D^*}$ is extracted from $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$, determined splitting the signal sample in:
  - **unpolarized** $\implies N_{sig}^{unpol} \propto a_{\theta_D}(q^2)$
  - **polarized** $\implies N_{sig}^{pol} \propto c_{\theta_D}(q^2)$
- $\cos\theta_D$ signal distribution corrected for reconstruction effect



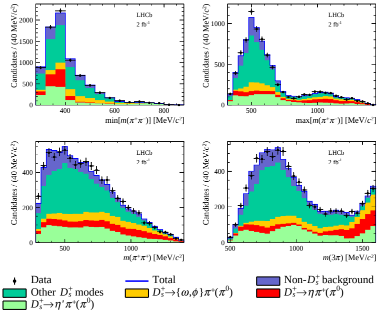
- $D^{*-}DX$ background templates determined from simulation
- Assuming no $F_L^{D^*}$ dependence on the D meson decay mode
- $\cos\theta_D$ distribution corrected through fully reconstructed control samples:
  - $D_s \to 3\pi^\pm$
  - $D^+ \to K^-2\pi^+$
  - $D^0 \to 3\pi^\pm K^-$



Modelling of D_s in $B \to D^{*-} D_s(X)$ decays

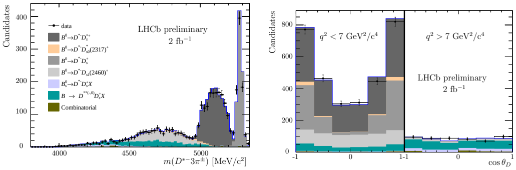
Decays of D_s [arXiv:2305.01463]

- $D_s \to 3\pi^{\pm} X$ branching fractions are not well known or correctly simulated
- Data sample selected using D_s BDT output
- Simultaneous fit to: $\min[m(\pi^+\pi^-)]$, $\max[m(\pi^+\pi^-)]$, $m(\pi^+\pi^+)$, $m(3\pi)$
- D_s fractions used to correct simulation



Production of D_s [LHCb-PAPER-2023-020]

- D_s meson arises from $B \to D^{*-} D_s^{+(*,**)} X$
- Poor knowledge on their relative fractions
- Enriched data sample of $D^{*-} D_s X$ decays reconstructed from $D_s \to 3\pi^{\pm}$ mode
- Fraction with respect the $D^* D_s^{*+}$ channel determined through a fit to the $m(D^{*-}3\pi)$
- Values are used to constrain the various component in the final fit



Extrapolation of $F_L^{D^*}$ on simulated sample (III)

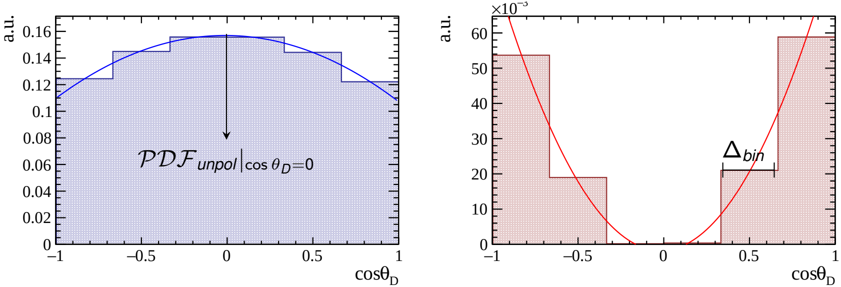
- $F_L^{D^*}$ can be determined using the equations in slide 10

$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

- a_{θ_D} and c_{θ_D} are directly related to the polarized and unpolarized yield

$$a_{\theta_D}(q^2) = N^{unpol} \cdot \mathcal{PDF}_{unpol}\big|_{\cos\theta_D=0}, \qquad c_{\theta_D}(q^2) = \frac{3}{2} N^{pol} \Delta_{bin}$$

signal $\cos\theta_D$ distribution



Signal fit results [LHCb-PAPER-2023-020]

- Signal yields from a 4D-binned template fit:
  - τ^+ lifetime (first row)
  - q^2 & $\cos\theta_D$ (second row)
  - anti-D_s BDT output (third row)
- Fit performed simultaneously on Run 1 and Run 2
- Results are integrated over Run 1 and Run 2

$F_L^{D^*}$ value extracted for the 3 q^2 region

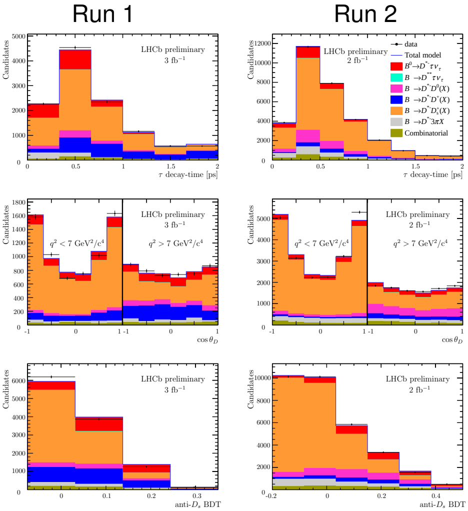
$$q^2 < 7\,\mathrm{GeV}^2/c^4 : \quad 0.51 \pm 0.07(stat) \pm 0.03(syst)$$

$$q^2 > 7\,\mathrm{GeV}^2/c^4 : \quad 0.35 \pm 0.08(stat) \pm 0.02(syst)$$

$$q^2\text{integrated} : \quad 0.43 \pm 0.06(stat) \pm 0.03(syst)$$

- All values are found to be compatible with the SM within 1σ
  - expected value in the integrated region ~ 0.44

[arXiv:1808.03565, arXiv:1805.08222, arXiv:1907.02257]



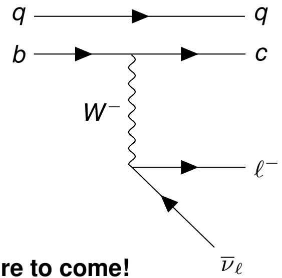
Systematic uncertainties [LHCb-PAPER-2023-020]

Source	low q^2	high q^2	integrated
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
TemplateSize	0.027	0.017	0.019
$\tau^+ \to 3\pi^\pm\pi^0$ fraction	0.001	0.001	0.001
D^{**} feed-down	0.001	0.004	0.003
Signal selection	0.005	0.004	0.005
Bin migration	0.008	0.006	0.007
$F_L^{D^*}$ in simulation	0.007	0.003	0.007
D_s decay model	0.008	0.009	0.009
$\cos\theta_D$ $D^{*-}D_s$	0.002	0.001	0.002
$\cos\theta_D$ $D^{*-}D_s^{*+}$	0.007	0.002	0.004
$\cos\theta_D$ $D^{*-}D_sX$	0.007	0.006	0.007
$\cos\theta_D$ $D^{*-}D^+X$	0.002	0.002	0.003
$\cos\theta_D$ $D^{*-}D^0X$	0.002	0.002	0.003
$F_L^{D^*}$ integrated	-	-	0.002
Total	0.036	0.023	0.029

Dominant source of systematic are:

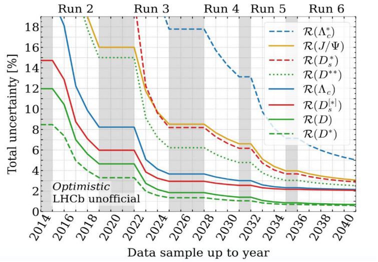
- Limited size of the simulation samples
- Form factor parameterization
- Modelling of the D_s
- $\cos\theta_D$ shape in $D^{*-}D_sX$ backgrounds
- Bin migration
- Signal acceptance
- Form factor model

Conclusions



- Recent results from semileptonic LFU decays at LHCb
  - $R(D) - R(D^*)$ with muonic τ decays
  - $R(D^*)$ with hadronic τ decays
- **Combined** $R(D) - R(D^*)$ is still a **3.2**σ tension from the SM
- **First measurement of** $F_L^{D^*}$ with hadronic τ decays
  - smallest statistical uncertainty and performed in two q^2 bins
- $F_L^{D^*}$ compatible with the SM expectation

More to come!



- $R(D^*)$ hadronic & $F_L^{D^*}$ with full Run 1 & Run 2
- Many LFU analysis: $R(D^0)$, $R(D^+)$, $R(D_s)$, $R(D^*)_e$
- Full angular analysis to determine spin and structure of NP
- LHCb Upgrade era has started:

  $\Longrightarrow$ **exciting time ahead!**

  (**See Federica Oliva's & Alessandro Minotti's talks on Friday**)

Thank you for your attention!

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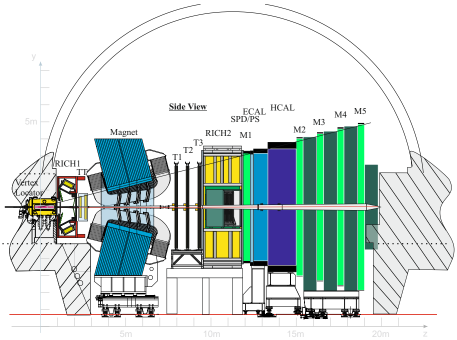
Backup

The Large Hadron Collider beauty (LHCb) Experiment

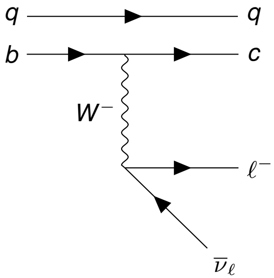
- LHCb detector is a single-arm forward spectrometer optimized for *b* and *c* hadron physics
  - pseudorapidity range: [2,5] $\Longrightarrow \sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
  - Run1 (2010-2012) $\Longrightarrow \approx 3\ \text{fb}^{-1}$
  - Run2 (2015-2018) $\Longrightarrow \approx 6\ \text{fb}^{-1}$

- Excellent performances [Int. J. Mod. Phys. A 30, 1520022 (2015)]:
  - **Momentum resolution**: $\frac{\sigma_p}{p} \approx 0.5 - 0.8\%$ ($p < 100$ GeV/c)
  - **Impact Parameter (IP) resolution**: $\sigma_{IP} \approx 20\ \mu m$ (at high p_T)
  - **Decay time resolution**: $\sigma_t \approx 50\ fs$
  - **Particle Identification (PID)**: $\varepsilon(K) \approx 95\%, \pi$ mis-ID $\approx 5\%$ ($p < 100$ GeV/c)
    $\varepsilon(\mu) \approx 97\%, \pi$ mis-ID $\approx$ 1-3%



Semileptonic decays at LHCb

- Tree level ⟹ abundant
- Theoretically clean
  - factorize hadron and lepton current
  - hadron current described by form-factors
- Experimentally tricky due to ≥ 1 missing ν_ℓ



Advantages

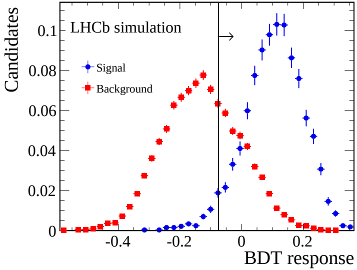
- Large H_b production
- Produce B^+, B^0, B^0_s, B^+_c, Λ^0_b, etc.
- Boosted H_b
- Efficient tracking ⟹ isolation

Challenges

- No beam-energy constraint
- Significant backgrounds (combinatorial + partially reco)
- Reliance on simulation
  - large samples are required

Description of the anti-D_s BDT

- A dedicated BDT has been trained to suppress the abundant $B \to D^* D_s X$ background
- Trained performed separately for Run 1 and Run 2 data
- Signal described via simulated $B^0 \to D^{*-} \tau^+ \nu_\tau$ decays, corrected for data/MC differences
- Background described using simulated sample of $B \to D^* D_s X$ decays, where the D_s decays in 3π
- Output used in final fit to control $D^* D_s X$ background



[Phys. Rev. D 97, 072013]

Input features

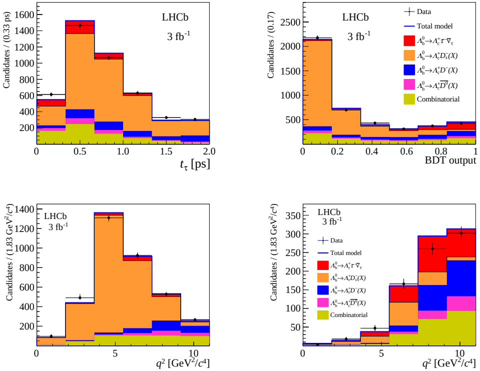
- Output of the isolation algorithms
- Momenta, masses and quality of the reconstruction of the decay chain under the signal and background hypotheses
- Masses of oppositely charged pion pairs
- Energy and the flight distance in the transverse plane of the 3π system
- Mass of the total system

$R(\Lambda_c^+)$ hadronic at LHCb [PRL 128, 191803]

- First LFU test in baryonic $b \to c\ell\nu_\ell$ decay with Run 1 data using hadronic $\tau \to 3\pi^\pm(\pi^0)$ decays

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^-\nu_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi^\pm)}, \qquad R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+)\left\{\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi^\pm)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu m \nu_\mu)}\right\}_{external}$$

- Fit performed using 3D binned template to extract the signal yield:
  - $q^2 \equiv (p_{\Lambda_b^0} - p_{\Lambda_c^+})^2$
  - τ decay-time
  - anti-D_s BDT output, trained to remove $\Lambda_b^0 \to \Lambda_c^+ D_s(X)$ decays
- Dominant background:
  - prompt $\Lambda_b^0 \to \Lambda_c^+ 3\pi^\pm X$
  - double charm $\Lambda_b^0 \to \Lambda_c^+ D_{(s)}(\to 3\pi^\pm X)X'$



$$R(\Lambda_c^+) = 0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$$

Agreement within 1σ with SM prediction